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WOOD AND OTHER RENEWABLE RESOURCES

LCA for assessing environmental benefit of eco-design strategies and forest wood short supply chain: a furniture case study

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Abstract

Purpose Eco-innovation strategies are increasingly adopted to ensure the minimization of environmental impacts. Nonetheless, only a comprehensive integrated assessment along the life cycle stages of a product may ensure a robust analysis of the benefit of the innovation. The object of the present study is the environmental assessment of furniture prototypes produced using certified wood and integrating eco-design criteria in their conception. The aim of the study was twofold: firstly, to evaluate the environmental profile of the furniture, highlighting possible hot spots of impacts, and secondly, to evaluate the capability of life cycle assessment (LCA) to identify the environmental benefit associated to the adoption of eco-innovation strategies, such as the following: ensuring short supply chain from raw material to production; using wood coming from certified forests (according to PEFC scheme); and the implementation of eco-design principles, also associated with green public procurement requirements.

Methods LCA has been applied in a case study related to the wood furniture sector in the alpine region of Northern Italy. Every activity was modeled using primary data, related to the inputs and outputs of the processes, provided directly by the designers and by woodworking firms. Input data related to forestry activities and wood extraction were collected and processed in a previous phase of the study. The life cycle of a prototype school desk from the cradle-to-gate perspective was analyzed. A woodworking plant was examined in detail, dividing the whole manufacturing process into four phases: panels production, woodworking, painting and steel parts processing. The system boundaries included all the activities which take place inside the plant as well as energy inputs, transports and ancillary products used.

Results and discussion The results highlighted that the working phases showing the greatest environmental burdens were the production of solid wood panels and the processing of iron parts. No concerns about chemicals, glues and paints were raised, due to the eco-design principles implemented in the production of the furniture. The choice of a short supply chain allowed for drastic reductions in the impacts associated to long-distance transports. Three sensitivity analyses were carried out to test the robustness of results concerning the following: (1) glue options, (2) drying phase and VOC emissions, and (3) transport options.

Conclusions This study proves to which extent eco-design criteria implemented in practice improve the environmental performance of products. All positive effects due to decisions taken in school desk design and conception were supported by evidence.

Keywords Eco-design · Eco-innovation · Furniture · Life cycle assessment · Short supply chain · Wood

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1 Introduction

An efficient and sustainable use of resources requires an integrated assessment of the various aspects related to their exploitation, use and end of life, adopting life cycle thinking as a prominent approach. Amongst others, biotic resources are considered as a key element of green economy and, especially, bio-economy. The sustainability of natural capital use, represented by human appropriation of resources, needs to be evaluated in order to avoid resource depletion and quality

degradation and in light of the need of maintaining the biosphere's regenerative capacity (Borucke et al. 2013). Forest-based products and related industries represent one of the most important economic sectors in the European Union (EU), accounting for about 10 % of the total manufacturing industries. The forest wood supply chain is a complex system and groups several different sectors, such as pulp and paper, paper and board, graphic industry, woodworking and furniture (Gonzalez-Garcia et al. 2009). In EU, wood product manufacturing or woodworking industries include the production of sawn wood, wood-based panels and other wooden products, such as joinery and carpentry materials, containers and other wooden packaging and articles. Besides, wood products are generally perceived as one of the most sustainable types of construction and consumer products. In terms of lifestyle and design, wood has many advantages over other materials (EC 2012). Wood is considered as a favourable renewable material, due to the low relative resource input necessary for its extraction (Werner and Nebel 2007). The growing interest of the public towards more sustainable ways of life, as well as production and consumption patterns, has led to the design of products with lower environmental and social impacts and to stricter regulations in developed countries regarding products' manufacturing, use and end of life (Gonzalez-Garcia et al. 2011). A survey conducted amongst a sample of Italian consumers showed that one third would pay 10 % over the standard price for a piece of furniture with more environmentally friendly features than a standard one (Federlegno 2010).

Hence, a proper evaluation of this industry sector to improve the environmental and the overall sustainability of the whole supply chain is of paramount relevance. Life cycle assessment (LCA) has been identified as one of the most reliable methodologies for evidencing and analyzing the environmental impacts along the life cycle of a product and should be part of the decision-making process towards more environmentally friendly products (ISO 14040 2006; ISO 14044 2006; Baumman and Tillman 2004). Many life cycle assessment studies proved that wood products usually have favourable environmental profiles compared to products from other materials with the same function (e.g. Werner and Richter 2007; Glover et al. 2002). Despite the strategic capabilities of LCA in assessing impact along the life cycle of a product, Werner and Richter (2007) found that the LCA database regarding furniture is very rudimentary. Mostly, LCAs for the wood and construction sectors focus on panels and boards production (Gonzalez-Garcia et al. 2009; Rivela et al. 2006; Rivela et al. 2007) and on the comparison of sustainable performance of wood furniture applying eco-design principles (Gonzalez-Garcia et al. 2011; Babarenda Gamage et al. 2008, Bovea and Vidal 2004). Bol et al. assess garden chairs (1995) and Nedermark (1998) different options for TV chassis. Michelsen and Magerholm (2010) provided a tool to improve the environmental performance for small- and medium-sized enterprises active in the furniture sector. Tarantini et al. (2011) applied LCA methodology for the definition of green public procurement (GPP) criteria of building products. González-García et al. (2012) studied the environmental profile of a set of wood furniture to define the most effective criteria for its eco-design: life cycle assessment (LCA) and Design for Environment (DfE) approaches were combined in order to propose improved alternatives. The production of the wooden boards and electricity were the sources of the major environmental burdens. Subsequently, the authors proposed related improvement alternatives for the eco-design process.

In this study, we performed an LCA of an entire wood furniture supply chain, focusing on a specific case in which a short supply chain was foreseen, and eco-innovation and eco-design principles were implemented. Firstly, we assessed the environmental profile of forest operations (Mirabella et al. 2014), evaluating different technological options, in order to evaluate the environmental sustainability of the raw material extraction process; secondly, in this paper, we focused on a wood-manufactured product (a school desk) aiming at the following: (1) evaluating the environmental profile of the furniture, highlighting possible hot spots of impacts, and (2) testing the capability of LCA to identify the environmental benefits associated to the adoption of a short supply chain, the use of wood coming from certified forests, and the implementation of eco-design principles. The potential impacts all along the production steps were analyzed, considering all stages from the conception of the product until the factory gates (cradle-to-gate analysis).

The paper is structured as follows: Section 2 provides the problem definition related to environmental sustainability of furniture with a specific focus on a case study. Section 3 presents the application of LCA illustrating life cycle assessment stages, goal and scope, functional unit, system boundaries and inventory. The impact assessment phase as well as results and discussion are provided in Sections 4 and 5, respectively. Conclusions and future outlook are presented in Section 6.

2 Environmental sustainability of furniture

2.1 Eco-design and eco-innovation principles implemented in the furniture sector

To ensure a satisfactory product from the environmental point of view, firms must start from its design conception. The design phase is responsible for 70 % of the final cost, functional requirements and environmental impacts of a product (Jeswiet and Hauschild 2004). Decisions made in this phase are very important since they influence the product up to its end of life; therefore, eco-design strategies are crucial to

reduce the inherent environmental burdens associated with a product (Gonzalez-Garcia et al. 2011; Jeswiet and Hauschild 2004). Several aspects are taken into account in eco-design for furniture. The main concerns regard the proper use of wood raw materials, the optimization of resources and recovery of wood scraps, the minimization of energy consumptions, proper use of chemicals, facility of dismantling and packaging reductions (Federlegno 2010; Gonzalez-Garcia et al. 2011). Key issues in realizing more environmentally friendly pieces of furniture are as follows: the use of solid wood, certified wood or ecological panels; reductions in the quantity of glue and paint or substitution with water-based ones; reductions of plastics and metals used, privileging the use of steel; and dematerialization and mono-materiality. Furniture produced following these criteria is found to reduce the overall impacts from 10 % to over 50 % (Ecofuture eco-friendly furniture 2004), while the eco-design strategies proposed by González-García et al. (2012) would allow reducing potential impacts up to 14 %.

To ensure reduced environmental impacts in furniture manufacturing, it is also very important to consider volatile organic chemicals (VOC) and formaldehyde emissions (Werner and Richter 2007; Gonzalez-Garcia et al. 2009; Bovea and Vidal 2004). The content of these chemicals in paint and glues should be minimized. This makes the painting and preservative treatment phases particularly critical. The reference document on Best Available Techniques (BAT) for surface treatment using organic solvents (European Commission EC 2007) advises manufacturers in choosing the best installations for the surface treatment of substances, objects or products using organic solvents. Other legislative reference points are the European Standards (ENs) and ISO standards that determine specific requirements for supply regarding public administration, such as furniture designed for schools. In this case, the criteria for establishing the suitability for use (stability, size requirements, resistance, colorimetry, etc.) and criteria related to environmental issues (especially for indoor hazardous substances such as formaldehyde) are defined. In addition, Green Public Procurement (GPP) is considered as a fundamental policy instrument in the framework of Sustainable Consumption and Production Policies of the European Union. Recently, a GPP strategy was set up by the European Commission, providing guidelines, training tools and renewing regulations to encourage public authorities to reduce the environmental impacts of their purchases through the use of more environmentally friendly products (Tarantini et al. 2011). Amongst these, specific criteria and minimum requirements for GPP of wood furniture were set (EC 2008). Due to high expenses of public authorities (equivalent to some 17 % of the EU's gross domestic product), public administrations have a great potential influence on their suppliers and manufacturers to produce better goods from an environmental point of view, and GPP is seen as a means able to create a more sustainable market (Tarantini et al. 2011).

2.2 Background of the case study

The presented case study refers to a wood forest short supply chain in Northern Italy (Lombardy region). According to the latest data available, Italy's timber and furniture industry in 2009 consisted of 73,618 firms with 396,964 employees, mainly in small- and medium-sized enterprises organized in industrial districts and 300 medium-structured enterprises. The timber and furniture industry, with 15 % of all businesses and 9 % of all workers in Italy's manufacturing sector, is the second biggest in Italy (Federlegno 2010). In Lombardy, it is possible to distinguish the following sectors: (1) forestry, (2) woodworking and (3) energy from biomass. The forest wood supply chain employs about 100,000 people, mostly in woodworking and related furniture sector.

An interdisciplinary project called *Bosco-Mobile*, Forest-Furniture (BOMO) was undertaken by the authors and partners to study the economic potential and viability of forests located in the region of Lombardy and to explore the environmental benefits associated with a short supply chain scheme, adopting eco-design criteria to improve environmental sustainability of the wood furniture industry. The project studied a pilot supply chain which used the wood from Intelvi Valley forests (Italian Alps in Lombardy) as input in the Lissone furniture district, only 60 km from the forest, i.e. within the boundaries for creating a short supply chain (all raw materials are produced in areas within 70 km).

Lissone is also located in Lombardy region (12 km from Milan). The town of Lissone and its surrounding area have always been linked to the history and culture of the furnishings. As one of the most representative and important consortium of firms in the furnishing industry of the region, "Progetto Lissone" was chosen as partner of the BOMO project and was responsible for the design and manufacturing of furniture produced with certified wood according to the Programme for the Endorsement of Forest Certification (PEFC) from Intelvi Valley.

2.3 Eco-design and eco-innovation principles applied to the case study (school desk)

Designing and manufacturing of BOMO furniture close the process chain that started with Intelvi Valley timber extraction, assessed in Mirabella et al. (2014). Following the criteria and principles presented in Section 2.1, design and manufacturing of furniture prototypes by Progetto Lissone started from a market analysis of the products commercially available, highlighting a lack of information—for the consumers—about the origin of raw materials and the possibility of disassembling the furniture after the use phase. A legislative analysis followed the previous one to identify the proper ergonomic and dimensional requirements for these kinds of products. Also, GPP criteria for wood furniture were taken into account

(European Commission 2008) to ensure the possibility for BOMO furniture to be eligible for being purchased by public administrations.

A preliminary analysis about the main requirements of the furniture to be designed and feasibility of applying the existing eco-design strategies led to the selection of the following criteria to be applied in the design of the BOMO furniture:

1. Multifunctional design (e.g. the chair can be easily converted into a chaise-longue)
2. Minimization of the number of components
3. Choice of raw materials and auxiliary materials/components with certified environmental features
4. Preference for short supply chains
5. Focus on ensuring disassembling and repairing (through single-component substitution)
6. Minimization of the use of raw materials with higher environmental impacts

The eco-design and eco-innovation principles have been implemented by the designers through the choices reported in Table 1.

3 Life cycle assessment and inventory of furniture

The environmental profile of the school desk was assessed through life cycle assessment, according to ISO 14040 (2006), and adopting ReCiPe (v.1.05) (Goedkoop et al. 2009) as impact assessment methods. Life cycle inventory phase involves the compilation and quantification of inputs and outputs of the system considered (ISO 14040 2006). The inventory and data collected, plus a final discussion about data quality and assumptions, are detailed in this section.

3.1 Objectives of the study

The scope of the work was the environmental analysis of a wood-based school desk that was designed following eco-design principles. Specific objectives of the evaluation were the identification of the following: (1) possible environmental hot spots for planning further actions towards impacts reduction and (2) potential benefits occurred by means of the choice of a short supply chain and the practical adaptation of eco-design and GPP criteria in school desk conception and manufacturing. The study covered the following: the supply of wood; the design; and all the steps of manufacturing, transports and energy consumption. It ended at the factory gate (cradle-to-gate analysis), since the subsequent stages were outside the scope of the project, and the supply chain was still in its pilot stage; furthermore, primary data about use and end of life were not available. Additionally, following the provisions general guide for life cycle assessment of the International Reference Life Cycle Data System (ILCD Handbook, EC-JRC 2010), we decided to not include carbon storage in the evaluation.

3.2 Functions and functional unit

The functional unit is the reference point to which inputs and outputs of the system under study are referred. The functional unit of the study is 1 school desk. Although the study is part of a wider evaluation which includes also the first part of the supply chain (forestry and logging activities, Mirabella et al. 2014), we chose two different functional units for the following reasons: (1) the evaluation should serve as a means to identify possible improvements, so it is important that results are scaled according to the objectives of the specific industry (i.e. wood in the case of forestry and pieces of furniture in the case of furniture manufacturing), and (2) the choice of two

Table 1 Eco-design strategies applied to BOMO furniture

Eco-design strategy	Implementation in BOMO furniture design
1. Multifunctional design	The chair can be easily used as chaise-longue, simply reverting it
2. Facilitate disassembling and repairing (through single components substitution)	Choice of a basic element, which is repeated to compose each piece of furniture. This allows to increase the durability and to help the future repairing and recovery of the elements
3. Minimize the number of components	Foster mono-materiality (wood-based furniture) Minimization of iron parts Exclusion of plastics
4. Promoting short supply chains	Use of local wood (transports within 70 km distance)
5. Privilege raw materials and auxiliary materials/components with certified environmental features	Use of the certified wood of Intelvi Valley, harvested following the best options for forestry operations as assessed in Mirabella et al. (2014)
6. Minimize the use of raw materials with higher environmental impact	Privilege of solid wood panels (SWPs) made up of three layers of wood (thickness 4–5 mm each) instead of particleboards Use of polyvinyl glues and water-based paints that guaranteed low emissions of VOC and formaldehyde neither during working nor during use phase

different functional units does not prevent the possibility of considering the entire forest wood furniture chain as a whole, because the inventory data of the first phase were used as inputs for the second phase, as it really happens in reality. Primary data about furniture manufacturing and referring to the production of 100 school desks were collected, in order to simulate a small-scale industrial production instead of a prototype phase. The carpentry firms involved in the chain were asked to make an estimation of energy and material consumption for the production of 100 school desks, starting from data about 1 desk made as a prototype. For instance, the energy consumption for each production stage of 1 desk was measured directly during the prototype manufacturing and was subsequently scaled up to 100 pieces according to the average ratio observed for the manufacture of other wooden products. The flows (emission and resources) were then referred to the functional unit (1 desk). This down-scaling was needed to avoid the risk of overestimating material and energy consumption (since in the prototype stage, the production is less efficient and may involve higher consumption of materials and energy). Three different tree species (maple, beech and ash) were used for the production of panels and subsequently school desk manufacturing; hence, it was necessary to refer all data and calculations to these. Average volumic mass was calculated and found to be equal to about 667 kg/m^3 of dried wood, moisture content of dried wood before manufacturing operations as assumed at 20 % (Hellrigl 2006). The school desk legs and working plane were made with solid wood panels (SWP), 15-mm thick, screws and supporting parts were made from iron (Fig. 1).

Fig. 1 BOMO school desk

3.3 Description of the system and boundaries

Progetto Lissone designed four pieces of school furniture according to BOMO project principles: one chair, one desk, one wardrobe and one bookcase. In this paper, the school desk production chain was taken as an example to assess the environmental impacts induced in a short supply chain scheme, as it is the most representative item for the scope of the study. All carpentry firms involved in school desk manufacturing were located in Lissone district. The pieces of furniture were made using the main raw material from the timber coming from the Intelvi valley, harvested from local forestry firms, part of the same short supply chain. Forestry operations, as other activities related to the production of raw materials, were part of the background system. They were modeled using primary data coming from a previous study (Mirabella et al. 2014). Wood drying is performed using natural air. System boundaries included the following: (1) production and acquisition of raw materials, (2) transports, (3) manufacturing phases, (4) energy consumption and (5) emissions along the production phases. The process chain can be subdivided into four main subsystems: (1) production of wood panels 60×140 cm (subsystem A), (2) woodworking manufacturing (subsystem B), (3) processing of iron parts (subsystem C), and (4) painting (subsystem D). The description of the system and its boundaries are reported in Fig. 2. The production and maintenance of capital goods were not included in the system boundaries, since these were considered negligible compared with their operational stages (SEMCo 2003; Rivela et al. 2006; Rivela et al. 2007). Wood scraps treatment was assumed as 50 % recycled and 50 % landfilling, according to the information received by the firms. In most European countries, scraps from woodworking are thermally utilized; however, this practice is not so common in small firms in Italy because the total amount of scraps produced by each company is relatively low. Therefore, there is not enough wood fuel available to make thermal use economically convenient. Data about wood wastes provided by the firms were uncertain, so we decided to assume the wood scraps treatment describing a mean situation. Table 2 details all data and processes used in this study.

3.3.1 Subsystem A: wood panels production

During this phase, multilayer panels were produced to form the so-called solid wood panel (SWP). The panels constitute the starting item for the production of the school desk. The SWPs represent a type of semi-finished products, made from a variable number of layers of wood glued over one another, always in an odd number. The thickness is variable according to the requirements of use and varies from a few tenths of a millimeter, up to 4–5 cm. In this first phase, the timber coming from Lario Intelvese Forest Consortium (LIFC) firms in Intelvi Valley was taken to carpentry, where it was debarked

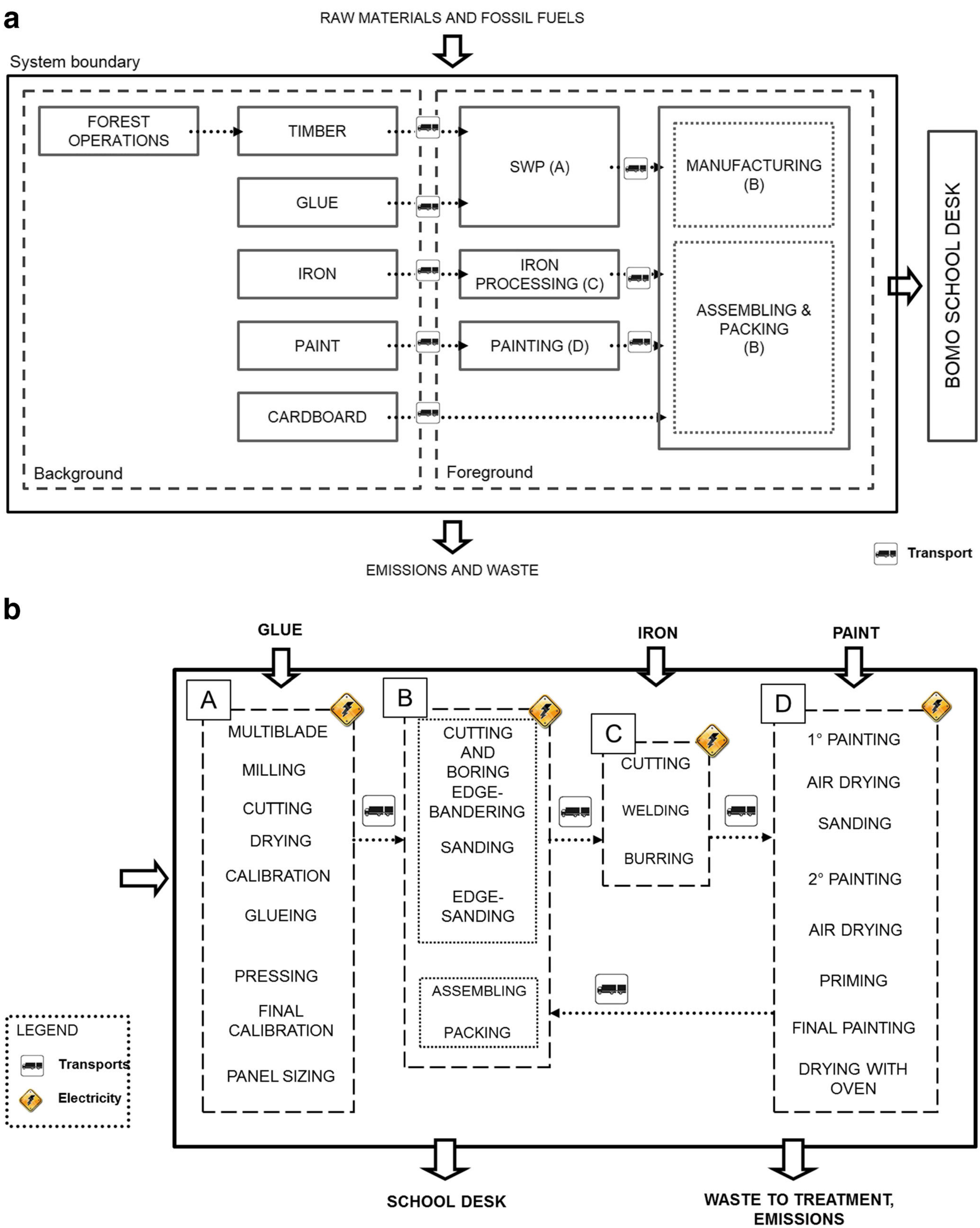

Fig. 2 **a** System boundaries of the process chain under study: BOMO school desk manufacturing. Distinction between background and foreground systems. **b** Details of the phases in the foreground system. *Letters* (*A*, *B*, *C*, *D*) *in square* refer to subsystems

Table 2 Global inventory for one BOMO school desk production. Data sources and assumptions

Data	Process/emission/waste	Database	Comment
Timber	1 t of timber from Intelvi Valley	BOMO 1	Results from first part of BOMO project are used
Iron	Cast iron	Ecoinvent v. 2.2	
Glue	Water-based glue	Company	Personal communication of production company
Paint	Water-based paint	Company	Personal communication of production company
Energy	Electricity, medium voltage, production IT	Ecoinvent v. 2.2	Energy consumption of machines
Emissions	VOC, volatile organic compounds	Ecoinvent v. 2.2	VOC emissions are only released during the process chain
Waste	Wood waste, Iron waste	Ecoinvent v. 2.2	Calculated from blueprints and verified by craftsmen
Disposal	Recycling wood, recycling steel and iron	Ecoinvent v. 2.2	Wood scraps are assumed to be recycled for 50 %
	Landfill of untreated wood, disposal, steel, 0 % water, to inert material landfill	Ecoinvent v. 2.2	Wood scraps are assumed to be disposed in landfill for 50 %
Transports	Transport, lorry 7.5–16 t, EURO3	Ecoinvent v. 2.2	Personal communication about lorry typology and distances by Progetto Lissone

and shaped for the next steps of manufacturing. Several work stages were performed (Table S1, Electronic Supplementary Material) and required the major amount of energy of the entire process. At this stage, it is very important to account for the quantity of glue used and its composition, since glues could represent an environmental hot spot due to its emissions in the operational and use phases. To minimize the related impacts, water-based glues are preferable, and these were chosen for panels manufacturing. Primary data about VOC emissions related to second drying phase of SWPs were not available; hence, they were calculated according to Puettman et al. (2010) that reports an amount of 1.37 kg of VOC emitted per cubic meter of hardwood. Other literature data reported a lower amount of VOC emissions (0.45 kg/ODT from Milota 2000) and were used to perform a sensitivity analysis (see Section 5). All details about inputs, outputs, energy consumption, transports and emissions are shown in Table S1 (Electronic Supplementary Material).

3.3.2 Subsystem B: woodworking manufacturing

This stage concerns all the operations involved in school desk manufacturing and the processes carried out on the SWP produced in the previous phase. The SWPs were cut into proper shape, edges were banded, and finally, the whole surface was sanded. Then, disassembled pieces of the school desk were transported to the painting site to be painted (see Section 3.3.4) and then were taken back to carpentry for the last two phases (assembling of the painted pieces and packaging). Packaged pieces of furniture were then sent to retailers. The details of inputs, outputs, energy consumption and transports were shown in Table S2 (Electronic Supplementary Material). Phases which did not involve the use of equipment (such as edge sanding, assembly and packing) were added in Table S2 (Electronic Supplementary Material) for completeness, but no inventory data was associated.

3.3.3 Subsystem C: processing of iron parts

This stage involves all operations performed on iron parts to shape them and to obtain pieces suitable to the production of BOMO school desks. Iron parts entered the plant and underwent cutting, welding and burring operations. Iron pieces were transported to the painting plant. A 50 % of iron scraps recycled and 50 % sent to landfill was assumed, according to the information received by the firms. As in the case of wood scraps, uncertainties related to iron wastes were high; hence, we decided to assume a mean situation occurring in the companies, based on the current fate of waste in Italy. The details of inputs, outputs, energy consumption and transports are shown in Table S3 (Electronic Supplementary Material).

3.3.4 Subsystem D: painting

Painting is the last phase involved in school desk manufacturing. Here, wood pieces coming from carpentry were painted with natural paints and using the most efficient available methods. Several phases of painting alternate the drying phases, both natural and with oven. Painted wood pieces were transported to carpentry for final assembling and packaging. The details of inputs, outputs, energy consumption and transports were shown in Table S4 (Electronic Supplementary Material). Phases which did not involve the use of equipment (i.e. electric consumption) and the wood pieces used were added in Table S4 (Electronic Supplementary Material) for completeness, but no inventory data was associated, and double counting of wood was avoided.

3.4 Data quality and assumptions

Data related to inputs, outputs, energy consumption and emissions are all primary data and were collected through meetings with designers and on-site measurements, while secondary

data relate to the processes used (see Table 1), country-specific electricity mix and transports. Primary inventory data were collected by partners, while Ecoinvent v. 2.2 was the main source of secondary data. The carpentry firms involved in the project are four and are the ones responsible for each phase of the manufacturing of the school desk components and of the assembling of the school desk: SWP producer (phase A), the craftsmen responsible for the woodworking activities (such as shaping and refinement of the single components made from the SWP; phase B), the manufacturer of the irony components of the desk (legs; phase C), and the craftsmen responsible for the final part of the manufacturing process, i.e. painting and assembling of the desk (phase D). Data provided were as follows: quantity of materials (SWP, paint and other chemicals), amount of discards (e.g. percentage of SWP not utilized) and energy consumption for each phase. Energy consumption consists only of the use of grid electricity needed to operate sawing and painting machines, and it was calculated considering the nominal power of machines multiplied for the number of hours needed to process each part of the desk. Concerning forest activities and timber used to manufacture the school desk, inventory data were taken from Mirabella et al. (2014). Due to a lack of data related to glue and paints production, it was necessary to model them, based on patents and information given by the companies. It was not possible to report the inventory data regarding the paints used to realize BOMO school desks, since this information was considered sensitive by the producers. Glues used were polyvinyl acetate, water-based. Indeed, this kind of glue shows better environmental performance compared to polyurethane glues. Their formulation is formaldehyde free, and VOC emissions are null. Primary data were not available, and it was not possible to obtain further details from the producers; hence, it was necessary to refer to literature data (US Patent 1971). There was also no data available regarding sawdust and wood particles released during manufacturing. Informal communications by experts declared that the amount of particles and sawdust was negligible, and emissions were treated through emissions treatment; this is confirmed also by other studies (Piccazzo 2006). The most critical emissions are known to come from VOC and formaldehyde released during drying, glueing, painting and use stages (Puettman et al. 2010; Gonzalez-Garcia et al. 2009; Vogtländer et al. 2010); hence, these were included in the study.

4 Life cycle impact assessment and results

An LCA for school desk manufacturing was carried out implementing Recipe 2008 (v.1.05) as an impact assessment method, incorporated in SimaPro 7.2. All impact categories defined by Recipe were analyzed in this study. Mandatory assessment stages of LCA methodology (classification, characterization) were considered. The impact categories considered in this study were as follows: climate change (GWP), ozone depletion (OD), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF), ionizing radiation (IR), terrestrial acidification (TA), freshwater eutrophication (FEP), marine eutrophication (MEP), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FE), marine ecotoxicity (ME), agriculture and urban land occupation (ALO and ULO), natural land transformation (NLT), water and metal depletion (WD and MD) and fossil depletion (FD).

4.1 Characterization stage at midpoint

Figure 3 shows the results for the characterization step. Absolute results are reported in Table 3. Phases with major environmental burdens were related to subsystem A (SWP manufacturing) and subsystem C (processing of iron parts), for 8 and 7 impact categories out of 18, respectively. The highest influence of subsystem A is not surprising, due to its numerous working phases and subsequent high electricity use, which here reached a peak value (about 11 kWh per FU). Categories most affected by subsystem A were as follows: climate change, ozone depletion, photochemical oxidant formation, terrestrial acidification, agricultural land occupation, natural land transformation and fossil depletion. For categories more affected by this subsystem, potential impacts ranged from 33 % (natural land transformation) to 55 % (agricultural land occupation). Regarding subsystem C, energy consumption was relatively low compared to other work stages (1.31 kWh per FU), and the only raw material input is iron; hence, it could be deduced that the production process of iron has the greatest share of environmental burdens. Impacts associated to subsystem C were as follows: human toxicity, particulate matter formation, ionizing radiation, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity and metal depletion. Potential impacts related to subsystem C ranged from 27 % (particulate matter formation) to 88 % (metal depletion). The contribution analysis of each subsystem shows that subsystem D (painting phase) also presents some criticisms. Categories most affected were marine eutrophication and terrestrial ecotoxicity, for 32 and 45 %, respectively. Painting phase was the third contributor to the environmental burdens of the system studied, and its results were sometimes comparable to those referred to subsystem C. However, due to uncertainties related to the quality of data, it was decided to focus a further evaluation only to subsystem A and C, as reported also in other studies (González-García et al. 2012).

In order to have detailed information about the contribution of each subsystem and each process to the different impact categories, i.e. to have useful information about the stages that can be improved upon, a detailed contribution analysis for

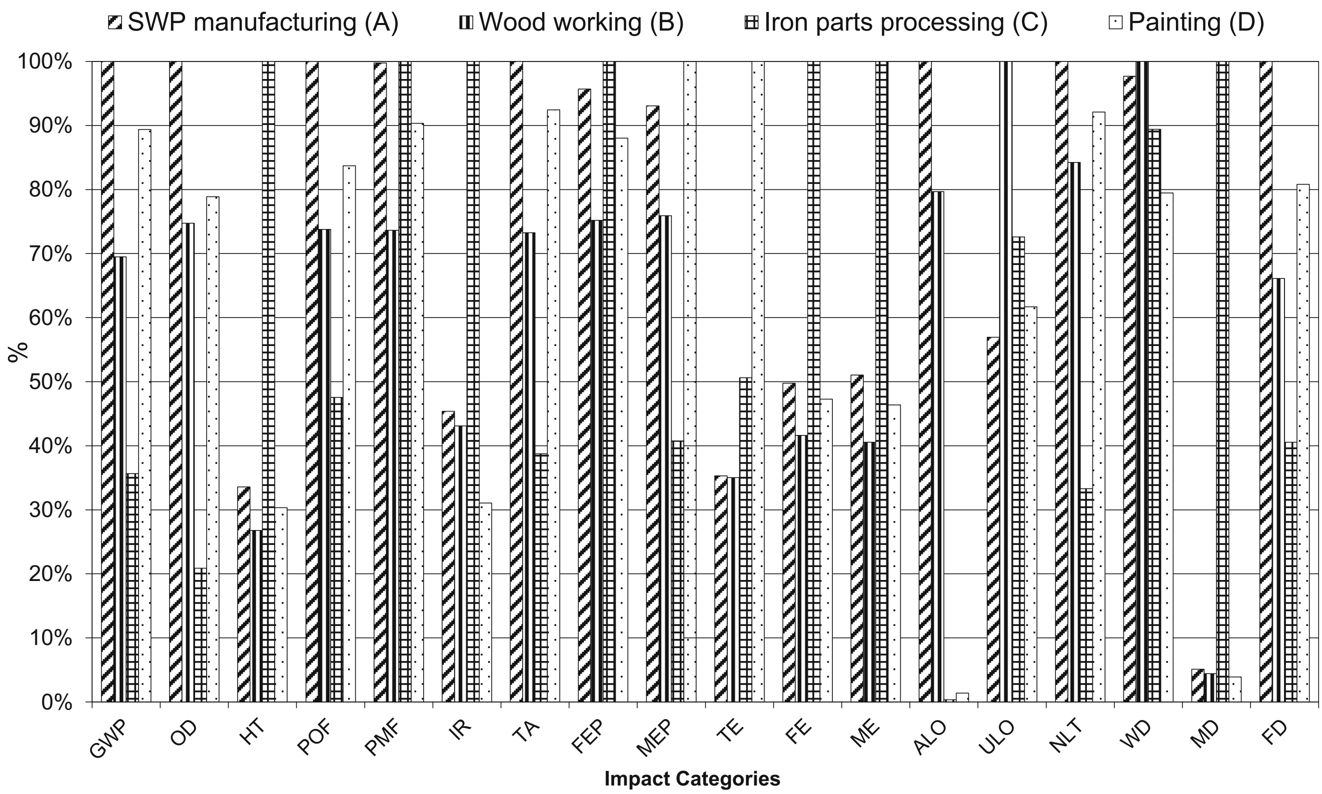

Fig. 3 Impact assessment results (characterization) for each working stage of BOMO school desk manufacturing. Acronyms used for the impact categories are explained in the text. *Letters in brackets* refer to subsystems

each impact category considered was carried out. Results of the analysis for the major contributors amongst the four subsystems were reported and discussed in the following paragraphs.

Table 3 Absolute results of characterization with Recipe Midpoint (H) Europe. Results referred to the F.U. For each indicator, the highest contribution is in italics

Impact category	Unit	A—wood panels production	B—woodworking manufacturing	C—processing of iron parts	D—painting	Total
Climate change	kg CO_{2eq}	*9.62E+00*	6.69E+00	3.43E+00	8.60E+00	2.83E+01
Ozone depletion	kg CFC-11_{eq}	*8.07E−07*	6.03E−07	1.68E−07	6.36E−07	2.21E−06
Human toxicity	kg 1.4-DB_{eq}	1.17E+00	9.36E−01	*3.49E+00*	1.06E+00	6.66E+00
Photochemical oxidant formation	kg NMVOC	*2.35E−02*	1.73E−02	1.12E−02	1.97E−02	7.16E−02
Particulate matter formation	kg PM_{10eq}	*1.03E−02*	7.57E−03	*1.03E−02*	9.29E−03	3.74E−02
Ionizing radiation	kg U_{235eq}	2.19E−01	2.08E−01	*4.84E−01*	1.50E−01	1.06E+00
Terrestrial acidification	kg SO_{2eq}	*3.33E−02*	2.44E−02	1.29E−02	3.08E−02	1.01E−01
Freshwater eutrophication	kg P_{eq}	1.55E−03	1.22E−03	*1.62E−03*	1.43E−03	5.81E−03
Marine eutrophication	kg N_{eq}	7.48E−03	6.10E−03	3.28E−03	*8.04E−03*	2.49E−02
Terrestrial ecotoxicity	kg 1.4-DB_{eq}	4.96E−04	4.92E−04	7.11E−04	*1.41E−03*	3.11E−03
Freshwater ecotoxicity	kg 1.4-DB_{eq}	2.33E−02	1.95E−02	*4.68E−02*	2.21E−02	1.12E−01
Marine ecotoxicity	kg 1.4-DB_{eq}	2.54E−02	2.01E−02	*4.97E−02*	2.31E−02	1.18E−01
Agricultural land occupation	m^2a	*2.08E+01*	1.66E+01	7.43E−02	2.88E−01	3.78E+01
Urban land occupation	m^2a	1.97E−02	*3.46E−02*	2.51E−02	2.14E−02	1.01E−01
Natural land transformation	m^2	*1.51E−03*	1.27E−03	5.03E−04	1.39E−03	4.68E−03
Water depletion	m^3	2.42E−02	*2.48E−02*	2.22E−02	1.97E−02	9.09E−02
Metal depletion	kg Fe_{eq}	8.51E−02	7.36E−02	*1.67E+00*	6.52E−02	1.89E+00
Fossil depletion	kg oil_{eq}	*2.90E+00*	1.92E+00	1.18E+00	2.35E+00	8.34E+00

4.1.1 Climate change (GWP)

SWP manufacturing was the working stage that most strongly affects climate change, mainly due to airborne emissions of CO_2 (78 %) and methane (about 11 %). These emissions were related to natural gas (responsible for 29 % of the overall emissions), hard coal (16 %) and heavy fuel oil (15 %) production. Woodworking was the second main contributor, with emissions of CO_2 (78 %) and methane (about 11 %) and natural gas, hard coal and heavy fuel oil production in the same proportions as subsystem A.

4.1.2 Ozone depletion (OD)

As shown in Fig. 3, SWP manufacturing and painting were the main contributors to ozone depletion, mainly due to airborne emissions of Halon 1211 (about 60 % of contribution for SWP manufacturing and 65 % for painting) and Halon 1301 (about 38 % SWP manufacturing and 32 % painting). The processes primarily involved for this category resulted to be the transport of natural gas through pipelines (35 % SWP manufacturing and 33 % painting) and crude oil production (12 % SWP manufacturing and 14 % painting).

4.1.3 Human toxicity (HT)

As reported in Fig. 3, subsystem C brought the most important environmental burdens for this impact category, due to mercury (60 %) and manganese release (24 %) during cast iron production (60 %) and disposal treatment of spoil in coal mining (17 %).

4.1.4 Photochemical oxidant formation (POF)

Subsystems A and D were the main sources of impacts in this category. Main contributors were airborne emissions of nitrogen oxides (75 and 77 %, respectively) and non-methane volatile organic compounds (NMVOC—12 and 9 %, respectively), released during the burning of heavy fuel in power plants (19 and 26 %), hard coal (17 and 19 %) and natural gas production (11 and 14 %). It is worthy to note that the emission of VOCs during the stage of second drying of the panels seems to be not relevant, even if it is reported as a possible hot spots in the literature about woodworking (Puettman et al. 2010; see also Section 5 for sensitivity analysis).

4.1.5 Particulate matter formation (PMF)

The working stages implying the greatest environmental burdens for PMF were processing of iron parts and SWP manufacturing. Considering the former, the main emissions regard $PM_{2,5\text{–}10}$ (contribution of 50 %), $PM_{2,5}$ (17 %) and sulphur dioxide (16 %). The emissions that most affected subsystem A were sulphur dioxide (45 %) and nitrogen oxides (37 %).

4.1.6 Ionizing radiation (IR)

As already found for the previous impact categories, subsystems C and A were responsible for the greatest environmental burdens for the IR category. The main contributors were radon 222 (67 % from subsystem C and 65 % from subsystem A) and carbon 14 airborne emissions (32 % from subsystem C and 33 % from subsystem A). Tailings in uranium milling and treatment of nuclear spent fuel accounted for 65 and 31 %, respectively, for subsystem C, 62 and 29 %, respectively, for subsystem A, related to the foreign energy mix used in Italy.

4.1.7 Terrestrial acidification (TA)

SWP production and painting working stages were responsible for most TA. The main contributors were sulphur dioxide (69 % in both cases) and (29 and 28 %, respectively). Processes mostly involved were as follows: heavy fuel oil (39 and 40 %), hard coal (25 and 27 %) and natural gas production (5 and 6 %).

4.1.8 Freshwater eutrophication (FEP)

Subsystems C and A were the least favourable stages for this impact category. This result was associated with the disposal of spoils of coal mining (63 and 80 %, respectively) and lignite (31 and 11 %). Phosphate-waterborne emissions represented almost the entire amount of pollutants released during this phase.

4.1.9 Marine eutrophication (MEP)

Major potential environmental impacts were associated with painting and SWP production, due to heavy fuel oil (22 and 25 %, respectively), hard coal (15 and 18 %) and natural gas production (15 and 17 %). Nitrogen oxides (74 and 92 %, respectively) and nitrates (23 and 4 %) represented the most important contributors.

4.1.10 Terrestrial ecotoxicity (TE)

As shown in Fig. 3, processing of iron parts was responsible for most TE, mostly due to cast iron production (79 %) and related emissions of mercury (58 %) and zinc (21 %). The second and third largest contributors were SWP production and the woodworking stage with emissions of phosphorus (43 and 35 %) and vanadium (23 and 18 %) related to heavy fuel oil production (35 and 26 %, respectively) and disposal of drilling wastes from gas and crude oil production (35 and 27 %).

4.1.11 Freshwater and marine ecotoxicity (FE and ME)

The highest potential FE and ME impacts were linked to subsystem C. For both categories, the main emissions causing the impacts were related to nickel (48 % for FE and 44 % for ME) and vanadium (29 and 27 %) releases. Disposal of slag generated during steel production (48 % for FE and 44 % for ME) and disposal of coal (29 % for FE and 26 % for ME) and lignite (16 % for FE and 12 % for ME) were the most impacting activities. The second largest contributor was subsystem A with emissions of nickel (53 % for FE and 47 % for ME) and manganese (21 % for FE and 18 % for ME) from disposal of coal (70 % for FE and 62 % for ME) and lignite mining (9 % for FE and 8 % for ME).

4.1.12 Agricultural land occupation, urban land occupation and natural land transformation

For these impact categories, Recipe 2008 v. 1.05 does not provide a proper characterization of impacts, but it just takes into account the surface area occupied or transformed (EC-JRC 2010). Related values for ALO, ULO and NLT are shown in Fig. 3 and are mainly due to occupation of forest soil (ALO, subsystem A), dump site (ULO, subsystem B) and transformation of forest area (NTL, subsystem A).

4.1.13 Water depletion

The woodworking stage represented the stage with the greatest environmental burdens for this category, followed by SWP production. Decarbonized water use in energy production was the main contributor to this category (45 % for subsystem B and 63 % for subsystem A). River water was identified as the main source used (77 and 64 %).

4.1.14 Metal depletion

Analyzing Fig. 3, subsystem C appeared as the greatest contributor to this impact category due to iron (96 %) and chrome (about 1 %) emissions related to iron extraction (97 %).

4.1.15 Fossil depletion

SWP production and painting caused the major potential impacts for this impact category, due to the large amount of gas (55 % subsystem A, 57 % subsystem D), oil (15 % subsystem A, 21 % subsystem D) and coal (15 % subsystem A, 17 % subsystem D) used for the production of the energy necessary. Natural gas (47 % for subsystem A and 44 % subsystem C) and crude oil production (20 % for subsystem A and 23 % subsystem C) accounted for the most FD.

5 Discussion

Previous LCA studies on furniture manufacturing (see for instance Bovea and Vidal 2004; Gonzalez-Garcia et al. 2011; González-García et al. 2012) identified the transport of wood, energy use for panel manufacturing and furniture assembling, the manufacturing of metal components and of the paintings used for finishing the pieces of furniture as the most relevant hot spots.

The results of the assessment on the BOMO school desk proved that the eco-design criteria applied helped to reduce some of these impacts, even if some critical issues remain to be improved. Absolute results of the characterization stage were compared with the results by González-García et al. (2012) about the LCA of a wooden-based modular social playground. The comparison needs to be carefully considered, for two main reasons: (1) the two products assessed are quite different, both in terms of dimensions (i.e. quantity of wood used) and of type and number of components, and (2) the methods used for the assessment are different (recipe for the present study, CML for the playground): Results were compared for the impact categories that are consistent in terms of unit of measurement between the two methods. Impacts were referred to 1 kg of each product in order to be compared.

BOMO school desk shows lower impacts for terrestrial ecotoxicity (6.11×10^{-5} vs 3.16×10^{-3} kg 1.4-DB_{eq}/kg), freshwater ecotoxicity (0.022 vs 0.044 kg 1.4-DB_{eq}/kg) and marine ecotoxicity (0.023 vs 75.56 kg 1.4-DB_{eq}/kg). Instead, it shows worst performance for impact categories highly affected from energy use and local electricity mix: terrestrial acidification (1.97×10^{-2} vs 1.76×10^{-2} kg SO_{2eq}/kg), ozone depletion (4.12×10^{-7} kg CFC11/kg vs 1.38×10^{-8}) and climate change (5.55 vs 1.40 kg CO_{2eq}/kg).

Regarding climate change impact, it is worthy to note that the BOMO school desk production chain highly reduces the CO_2 emissions related to the transport of timber (see the sensitivity analysis made about transport for details) thanks to a short supply chain. However, the total amount of greenhouse gas (GHG) emission from the production chain (calculated per kg od product) is higher than that of the average emission calculated in other similar chains (1.8 kg CO_{2eq}/kg; source: Gonzalez-Garcia et al. 2011). The higher amount of GHG emitted can be explained considering two main factors: (1) the extensive use of electricity in the firms of the BOMO production chain (mainly due to the fact that they are very small and the establishment of wood boilers or other energy equipment could be difficult) and (2) the fact that the industrial production is not yet in place, so the data about energy consumption could be overestimated.

According to the results presented in Fig. 3, SWP manufacturing and processing of iron phases were identified as the sources of major impacts for this process chain. For this reason, a further characterization was carried out, and

subsystems A and C were analyzed in detail. As shown in Fig. 4, energy consumption was the major source of impacts for subsystem A. This is due to the highly energy intensive processes needed to produce SWP, whose working phases were numerous. The phases that show the greatest environmental burdens are cutting, second drying and calibration that account for about 80 % of total energy consumption used for the subsystem A. Shares of impacts ranged from 62 % for ionizing radiation to 93 % for natural land transformation. Timber extraction significantly affected only the agricultural land occupation category (100 %), whereas the implications on other categories varied from 1 to 11 %. It is remarkable that glues, despite their low content in the final product, had a significant incidence for some categories (water depletion, fossil depletion, metal depletion, ionizing radiation), ranging from 16 to 34 %, but no toxicity was highlighted by this analysis, proving that polyvinyl glues are not impacting human health. The contribution of transport was always negligible, while disposal in landfills significantly affected the category climate change (16 %).

Subsystem C was the second larger contributor to the overall environmental impacts of the process chain. As for subsystem A, a detailed analysis was carried out, the results of which are displayed in Fig. 5. These results confirmed what was forecasted before: the greatest environmental burdens were mostly due to iron extraction, with a variable contribution ranging from 55 % (ozone depletion) to 100 % (metal depletion), but only for two categories, its influence was lower than 70 % (ozone depletion, natural land transformation). Energy consumption had a significant contribution only for two categories, and its incidence ranged from 3 to 45 %. Transports and disposal were found to be negligible.

This analysis proved some of the potential benefits induced on furniture manufacturing by applying eco-design criteria, since all major sources of impacts usually detected in traditional furniture evaluation (Ecofuture eco-friendly furniture 2004) resulted negligible in the present case study.

Energy consumption and iron parts processing were identified, as major sources of impacts, while chemicals, glues and paints did not account for significant impacts. This means that prioritizing the use of SWP rather than fibreboards or particleboards can increase electricity use caused by the numerous working phases, but it is more favourable concerning toxicity, since a lower amount of glues is used. In this regard, it would be important to maximize the energy efficiency of the system and to exploit a larger share of renewable energy forms, in order to decrease the environmental burdens related to electricity use during manufacturing. The second largest contributor, iron, was minimized in content, and the results proved

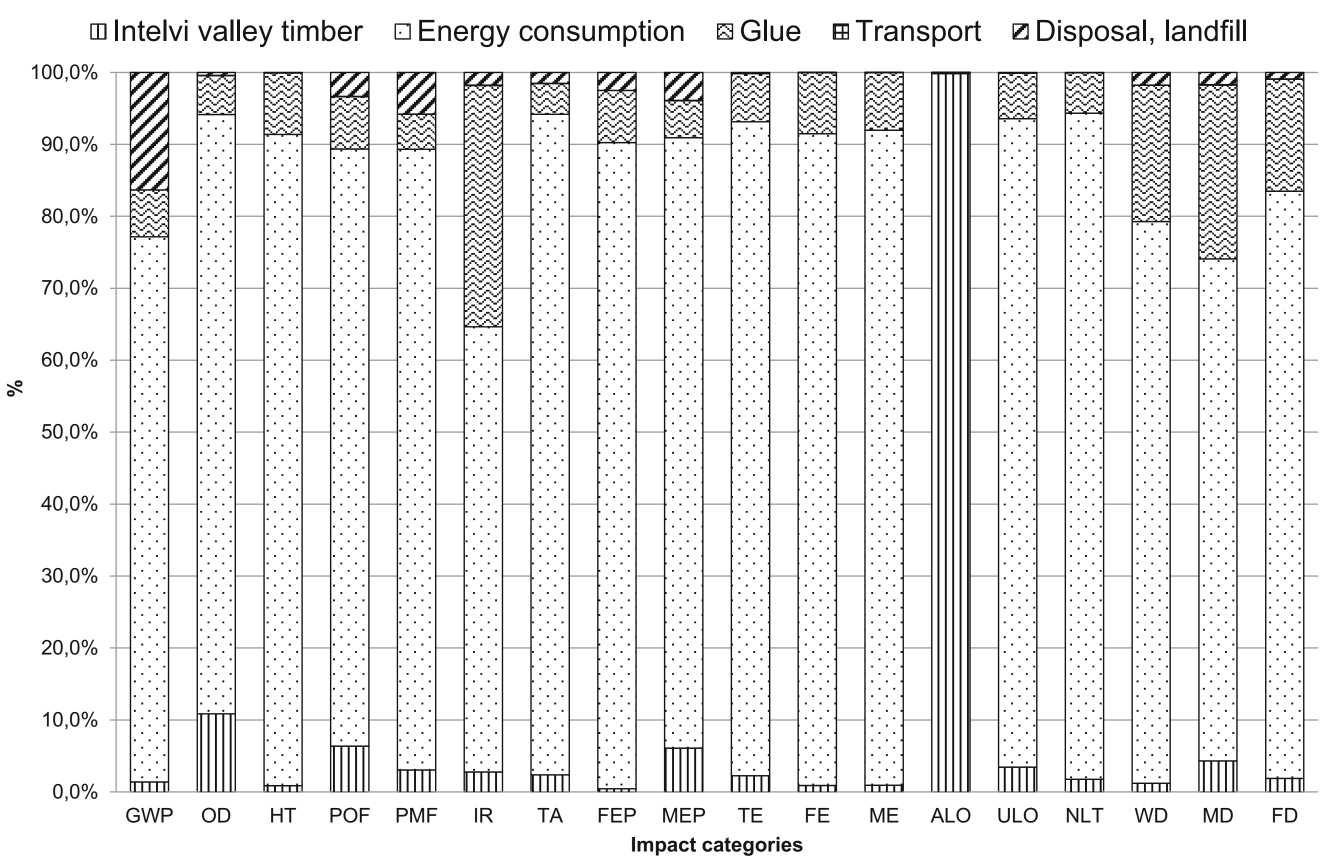

Fig. 4 Characterization of results for subsystem A of BOMO school desk manufacturing

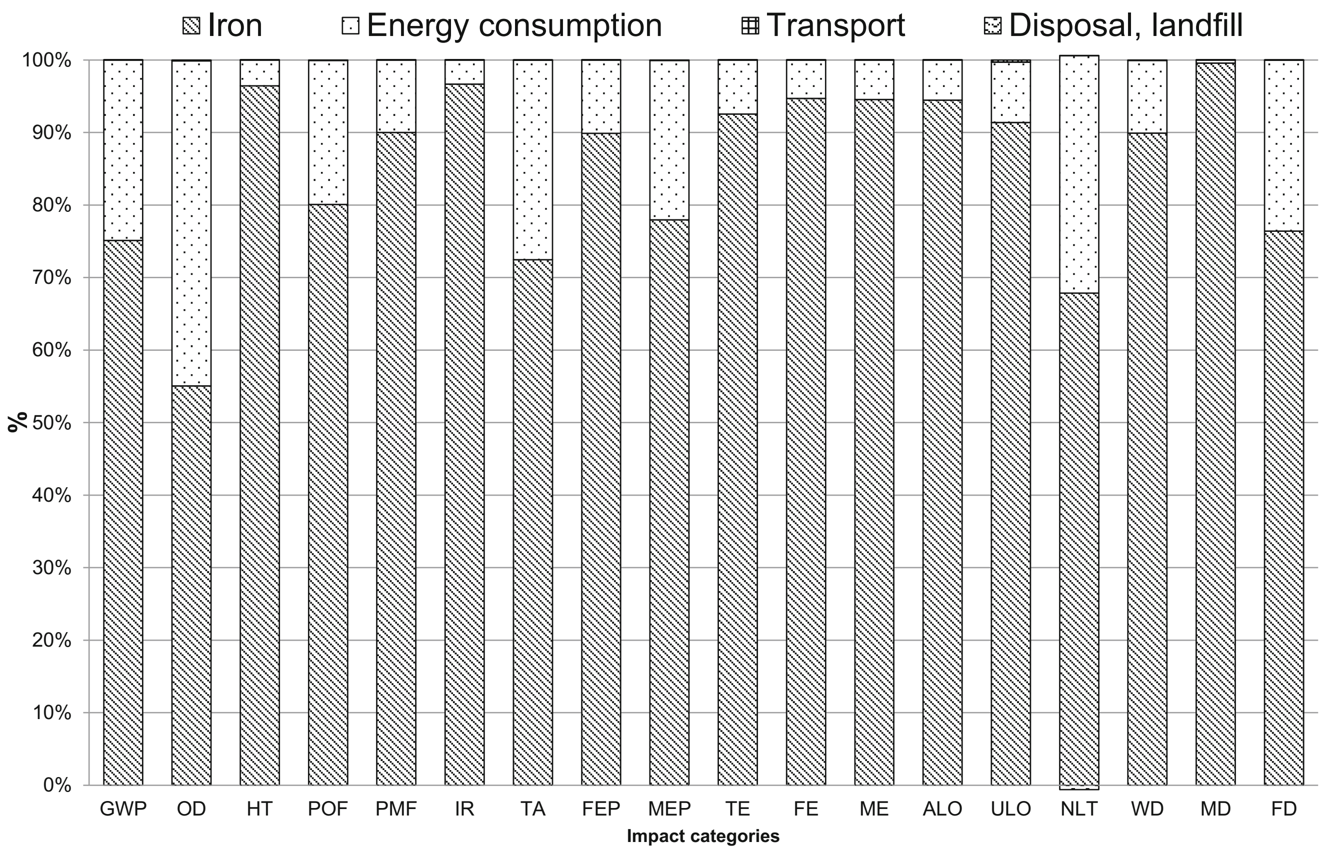

Fig. 5 Characterization of results for subsystem C of BOMO school desk manufacturing

the benefits induced by prioritizing mono-materiality as much as possible. Impacts related to transports were always negligible and further encouraged the implementation of short supply chain schemes. To check the robustness of these results, three sensitivity analyses were performed. In the first sensitivity analysis, water-based glue was substituted by a polyurethane glue. Even if a low amount of glue is used (Fig. S1, Electronic Supplementary Material), it is possible to notice that the use of water-based glue means an improvement of BOMO desk environmental performance in almost every impact category. Improvements range from 0.5 % (ME) to 19.2 % (IR). In the second sensitivity analysis, results obtained considering a lower amount of VOC emissions during second drying phase in subsystems A (0.45 kg/ODT from Milota 2000) were compared with the baseline scenario provided in Section 3.3.1. However, no significant differences were observed. Further studies and investigations should deal with primary data about VOC emissions during second drying phase. The third analysis was performed to highlight the environmental burdens incurred by long-distance transports of wood in the case of foreign timber imports, as reported in the first part of this study. Average distances along the whole supply chain (from forestry to furniture manufacturers) were considered in the evaluation and were equal to 70 km for Intelvi Valley timber (from Intelvi valley forests to Lissone furniture district) and 1,550 km for standard timber. Indeed, as discussed with local experts, the Lissone district usually buy timber from Central Europe or from Ukraine, due to its technological characteristics (more regular logs) and price, so the average distance considered for the standard timber was set at 1,550 km (Marra et al. 2011). Results are shown in Fig. S2 (Electronic Supplementary Material). The use of a standard wood supply chain has the greater environmental burdens in all impact categories. Improvements range from 16 % (POF) to 3 % (FE and HT).

As a final consideration, it is important to remark that it was not possible to assess the following: (1) the improvements due to the use of certified wood, since no standard procedures are currently available, and (2) the benefits associated to the end-use phase, which prefigures an easy disassembling of furniture, its recycling and recovery. Indeed, it was not yet possible to account for the benefits induced using the wood produced according to certification schemes (such as PEFC) through the LCA methodology. Forest certification is a single-issue label, and it only certifies the quality of forest management. So far, no specific inventories are available for certified wood, and at the impact assessment level, no impact assessment categories/characterization factors is accounting for lower/different impacts, e.g. in relation to land use and biodiversity-related impacts.

However, forest is a very complex system itself and can be difficult to be quantified as a component of an LCA (Straka and Layton 2010).

6 Conclusions and outlook

The design and production of BOMO school desk represent the last phase of a broader project, whose aim was to evaluate and to implement a sustainable forest wood furniture supply chain, using the wood resources of the Intelvi Valley (Lombardy, northern Italy). The aim was also to provide a short supply chain framework to verify to which extent it would be more environmentally friendly unlike to the traditional chains. One of the aims of an LCA analysis is to identify phases in the process chain responsible for the major environmental burdens; this allows for intervening and realizing improvements. The objective of this study was the evaluation of the benefits obtained applying eco-design criteria in furniture design and manufacturing and the detection of hot spots over the life cycle of a school desk (cradle-to-gate perspective). Its production within the BOMO project framework was analyzed in detail, proving the efficiency of eco-design criteria and identifying hot spots and possible improvements. All impacts related to the timber used were already minimized thanks to the results used from Mirabella et al. (2014): operational modes chosen were the most suitable for the area investigated and gave the best environmental performances. Moreover, the short supply chain guaranteed the minimization of impacts related to transports. Regarding the manufacturing, the design stage integrated eco-design principles as a basis to realize the prototypes. This means the use of panels with low content of glues, drastic reduction of iron parts, absence of plastics and water-based paints and special attention to the end-of-life stage (disassembling, recovery and reuse). Polyvinyl glues and water-based paints have very low emissions of VOC and formaldehyde, identified as one of the most critical hot spots in traditional furniture manufacturing and use. This was proved also by the three sensitivity analyses performed. The use of water-based glue instead of polyurethane glue means an improvement of BOMO desk environmental performance in almost each impact category, ranging from 0.5 % (ME) to 19.2 % (IR). The second sensitivity analysis showed no significant differences related to VOC emissions during second drying phase. Finally, the third analysis highlighted that the use of a standard wood supply chain has the greater environmental burdens in all impact categories compared to a short one.

Some final considerations are related to weak points in LCA and life cycle impact assessment (LCIA) and worth in-depth examination. The results of this case study was strongly local-dependent, but many local impacts and benefits were not accounted in LCA, since many LCIA model are not yet site-specific. For this reason, possible further benefits or local impacts could not be taken into account. Biotic depletion is not considered by several impact assessment methods; however, it is clear that overexploitation can be source of serious impacts. Further studies could address a sensitivity analysis to the evaluation of biotic depletion potential using different impact assessment methods. Acknowledging for the limits of the present evaluation, future research outlooks should be addressed towards a comprehensive environmental sustainability assessment, including the following aspects: (1) capability of LCA to thoroughly address potential benefits induced by using wood produced according to certification schemes (such as PEFC); (2) possible integration of the environmental sustainability assessment with other dimensions, e.g. the local supply chain and social and economic fallout on local employment and economy; and (3) more deep investigation of the role of wood as a raw material with reference to possible end-of-life scenarios.

Besides, widening the market of product manufactured following eco-design principles requires also that GPP potential is expanded, supporting the public authorities' purchases of products with excellent environmental profile.

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References

Babarenda Gamage G, Boyle C, McLaren SJ, McLaren J (2008) Life cycle assessment of commercial furniture: a case study of Formway LIFE chair. Int J Life Cycle Assess 13:401–411

Baumman H, Tillman AM (2004) The hitch hiker's guide to LCA. An orientation in life cycle assessment methodology and application. Studentenlitteratur, Lund, ISBN 9144023642

Bol B, Lenstra G, van Liebergen H, Paardekooper L (1995) Environment related comparative study on garden chairs (in German). Tebodin, B.V. im Auftrag des Fachverbandes Kunststoff-Konsumwaren im GKV, Frankfurt a.M.

Borucke M, Moore D, Cranston G, Gracey K, Iha K, Larson J, Lazarous E, Morales JC, Wackernagel M, Galli A (2013) Accounting for demand and supply of the biosphere's regenerative capacity: the National Footprint Accounts' underlying methodology and framework. Ecol Indicators 24:518–533

Bovea MD, Vidal R (2004) Materials selection for sustainable product design: a case study of wood based furniture eco-design. Mater Des 25:111–116

EC (2008) Green Public Procurement (GPP) product sheet—furniture. Available on: http://ec.europa.eu/environment/gpp/pdf/toolkit/furniture_GPP_product_sheet.pdf

EC (2012) Wood, paper, printing. Woodworking industry. Last update 2nd February, 2012. Available on: http://ec.europa.eu/environment/gpp/pdf/toolkit/furniture_GPP_product_sheet.pdf

EC-JRC (2010) International Reference Life Cycle Data System (ILCD) handbook—general guide for life cycle assessment—detailed

guidance. EUR 24708 EN. Luxembourg. Publications Office of the European Union

Ecofuture eco-friendly furniture (2004) The LIFE Environment project and the furniture sector. Available on: http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=LIFE04_ENV_IT_000588_LAYMAN.pdf. Last update 29th March, 2004 (accessed September 2012)

European Commission (EC) (2007) Reference document on Best Available Techniques on surface treatment using organic solvents. BREF IPPC BUREAU. Available at: http://eippcb.jrc.ec.europa.eu/reference/BREF/sts_bref_0807.pdf (accessed June 2012)

Federlegno Arredo (2010) Environmental report, third edition. Milano. In Italian, available on: http://www.federlegnoarredo.it/ContentsFiles/0000109913_RapportoA2010.pdf

Glover J, White DO, Langrish TAG (2002) Wood versus concrete and steel in house construction: a life cycle assessment. J Forest 100(8):34–41

Goedkoop MJ, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R (2009) ReCiPe 2008, a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I: Characterisation; 6 January 2009, http://www.lcia-recipe.net. (accessed July 2012)

Gonzalez-Garcia S, Feijoo G, Widsten P, Kandelbauer A, Zikulnig-Rusch E, Moreira MT (2009) Environmental performance assessment of hardboard manufacture. Int J Life Cycle Assess 14:456–466

Gonzalez-Garcia S, Silva FJ, Moreira MT, Castilla Pascual R, Garcia Lozano R, Gabarrel X, Rieredavalla i Pons J, Feijoo G (2011) Combined application of LCA and eco-design for the sustainable production of wood boxes for wine bottles storage. Int J Life Cycle Assess 16:224–237

González-García S, García Lozano R, Moreira MT, Gabarrell X, Feijoo G, Murphy RJ (2012) Eco-innovation of a wooden childhood furniture set: an example of environmental solutions in the wood sector. Sci Total Environ 426:318–326

Hellrigl B (2006) Elementi di xiloenergetica. In Italian, available on: http://www.aiel.cia.it/immagini/upload/ELEMENTIdiXILOENERGETICA_low.pdf accessed June 2012

ISO 14040 (2006) Environmental management—life cycle assessment—principles and framework. ISO, Geneva, Switzerland

ISO 14044 (2006) Environmental management—life cycle assessment—requirements and guidelines. ISO, Geneva, Switzerland

Jeswiet J, Hauschild M (2004) EcoDesign and future environmental impacts. Mater Des 26:629–634

Marra M, Castellani V, Mirabella N, Sala S, Negri M, Guercini S (2011) Technological characteristics and sustainability assessment of short forestry-wood chain for alpine hardwood furniture. 3rd International Scientific Conference on Hardwood Processing (ISCHP2011). October 16–18, 2011 Virginia Tech, Blacksburg, VA, USA (peer reviewed)

Michelsen O, Magerholm A (2010) Using eco-efficiency in sustainable supply chain management; a case study of furniture production. Clean Techn Environ Policy 12:561–570

Milota M (2000) Emissions from wood drying. Forests Prod J 50(6):10–20

Mirabella N, Castellani V, Sala S (2014) Forestry operations in the alpine context. Life cycle assessment to support the integrated assessment of forest wood short supply chain. Int J Life Cycle Assess. doi:10.1007/s11367-014-0756-8

Nedermark R (1998) Ecodesign at Bang & Olufsen. In: Klostermann J, Tukker A (eds) Product innovation and eco-efficiency; twenty three industry efforts to reach the factor 4. Kluwer Academic Publishers, Dordrecht, Boston, London

Piccazzo C (2006) Uso ecologico del legno. Corso di Principi di Ecodesign. Facoltà di Architettura, Università di Genova. In Italian, available on: http://www.arch.unige.it/did/l1/disegnoind/terzo0607/ecodesign/materialedid/usolegno.pdf accessed June 2012

Puettman M, Bergman R, Hubbard S, Johnson L, Lippke B, Oneil E, Wagner FG (2010) Cradle-to-gate life-cycle inventory of US wood products production: CORRIM phase I and phase II products. Wood Fiber Sci 42(CORRIM special issue):15–28

Rivela B, Hospido A, Moreira MT, Feijoo G (2006) Life cycle inventory of particleboard: a case study in the wood sector. Int J Life Cycle Assess 11:106–113

Rivela B, Moreira MT, Feijoo G (2007) Life cycle inventory of medium density fibreboard. Int J Life Cycle Assess 12:143–150

SEMCo, The Swedish Environmental Management Council (2003) Product-specific requirements (PSR) for preparing an environmental product declaration (EPD) for Product Group. Wood particleboards. PSR 2003:8. Available at: www.environdec.com

Straka TJ, Layton PA (2010) Natural resources management: life cycle assessment and forest certification and sustainability issues. Sustainability 2:604–623

Tarantini M, Dominici Loprieno A, Porta PL (2011) A life cycle approach to green public procurement of building materials and elements: a case study on windows. Energy 36:2473–2482

Vogtländer J, van der Lugt P, Brezet H (2010) The sustainability of bamboo products for local and Western European applications. LCAs and land-use. J Clean Prod 18:1260–1269

Werner F, Nebel B (2007) Wood & other renewable resources. Int J Life Cycle Assesess 12(7):462–463

Werner F, Richter K (2007) Wooden building products in comparative LCA. A literature review. Int J Life Cycle Assess 12(7):470–479